Precision Timing of Two Anomalous X-Ray Pulsars

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ABSTRACT

We report on long-term X-ray timing of two anomalous X-ray pulsars, 1RXS J170849.0−400910 and 1E 2259+586, using the *Rossi X-ray Timing Explorer.* In monthly observations made over 1.4 yr and 2.6 yr for the two pulsars, respectively, we have obtained phase-coherent timing solutions which imply that these objects have been rotating with great stability throughout the course of our observations. For 1RXS J170849.0−400910, we find a rotation frequency of 0.0909169331(5) Hz and frequency derivative $-15.687(4) \times 10^{-14}$ Hz s^{-1}, for epoch MJD 51215.931. For 1E 2259+586, we find a rotation frequency of 0.1432880613(2) Hz, and frequency derivative $-1.0026(7) \times 10^{-14}$ Hz s^{-1}, for epoch MJD 51195.583. RMS phase residuals from these simple models are only $\sim$0.01 cycles for both sources. We show that the frequency derivative for 1E 2259+586 is inconsistent with that inferred from incoherent frequency observations made over the last 20 yr. Our observations are consistent with the magnetar hypothesis and make binary accretion scenarios appear unlikely.

Subject headings: stars: neutron — Pulsars: individual (1RXS J170849.0−400910, 1E 2259+586) — X-rays: stars

1. Introduction

The nature of anomalous X-ray pulsars (AXPs) has been a mystery since the discovery of the first example (1E 2259+586) nearly 20 years ago (Fahlman & Gregory 1981). The properties of AXPs can be summarized as follows (see also Mereghetti & Stella 1995, van Paradijs, Taam, & van den Heuvel 1995, Gotthelf & Vasisht 1998): they exhibit X-ray

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pulsations in the range ∼5–12 s; they have pulsed X-ray luminosities in the range $\sim 10^{34} - 10^{35}$ erg s^{-1}; they spin down regularly within the limited timing observations available, with some exceptions; their X-ray luminosities are much greater than the rate of loss of rotational kinetic energy inferred from the observed spin-down; they have spectra that are characterized by thermal emission with $kT \sim 0.4$ keV, with evidence for a hard tail in some sources; they are found in the plane of the Galaxy; and two of the six certain members of the class appear to be located at the geometric centers of apparent supernova remnants (Fahlman & Gregory 1981, Vasisht & Gotthelf 1997). Soft gamma repeaters also exhibit AXP-like pulsations in quiescence (e.g. Kouveliotou et al. 1998).

Mereghetti & Stella (1995) suggested that AXPs are accreting from a low mass companion. However increasingly this model has become difficult to reconcile with observations. The absence of Doppler shifts even on short time scales (e.g. Mereghetti, Israel, & Stella 1998), the absence of a detectable optical/IR companion or accretion disk (see Mereghetti & Stella 1995), the apparent associations with supernova remnants, the apparent steady spin down within the limits of current observations (e.g. Gotthelf, Vasisht, & Dotani 1999), and AXP spectra that are very different from those of known accreting sources, all argue against an accretion origin for the X-rays.

Recently, it has been argued that the AXPs are young, isolated, highly magnetized neutron stars or "magnetars" (Thompson & Duncan 1996, Heyl & Hernquist 1997). Evidence for this is primarily the inferred strength of the surface dipolar magnetic field required to slow the pulsar down *in vacuo*: $\sim 10^{14} - 10^{15}$ G. The spin-down ages in this model, inferred assuming small birth spin periods, are in the range of ∼8–200 kyr. This suggested youth is supported by the two apparent supernova remnant associations. Additional circumstantial supporting evidence comes from AXPs location close to the Galactic plane, consistent with their being isolated neutron stars near their birth place, as well as from interpreting apparent deviations from spin-down as glitches (Heyl & Hernquist 1999) similar to those seen in radio pulsars (e.g. Kaspi et al. 1992). Recently, deviations from simple spin-down have been suggested, under the magnetar hypothesis, to be due to radiative precession, originating in the asphericity of the neutron star produced by the strong magnetic field (Melatos 1999).

One way to test both the magnetar and accretion models is through timing observations. The spin down of some AXPs has been monitored by considering the measured frequency at individual epochs (e.g. Baykal et al. 1998, Gotthelf, Vasisht, & Dotani 1999). However those measurements have been sparse and are only marginally sensitive to spin irregularities on time scales of weeks to months, relevant to glitches or accretion torque fluctuations. Further, high-precision determination of the spin evolution over a long baseline is necessary to look for "timing noise" as is seen in many young radio pulsars (e.g. Arzoumanian et al. 1994, Kaspi

et al. 1994, Lyne 1996), to obtain a reliable measurement of a braking index, and to search for precession (Melatos 1999). Whether such high precision is possible to achieve with AXP timing has not, until now, been established.

Here we report on X-ray monitoring observations made with the *Rossi X-ray Timing Explorer* (*RXTE*) in which, for the first time, we determine high-precision spin parameters using long-term phase-coherent timing of two AXPs. The sources, 1RXS J170849.0−400910 (Sugizaki et al. 1997, Israel et al. 1999) and 1E 2259+586 (Baykal & Swank 1996, Parmar et al. 1998, Baykal et al. 1998) have periods of 11 s and 7 s, respectively. The *RXTE* AXP monitoring project is part of a larger effort to time coherently several AXPs. Results for other sources will be presented elsewhere.

2. Observations and Results

Our observations were made using the *RXTE* Proportional Counter Array (PCA) (Jahoda et al. 1996). The detector consists of five identical multi-anode proportional counter units (PCUs) each containing a front propane anticoincidence layer followed by several xenon/methane layers. The detector operates in the 2–60 keV range, with a total effective area of $\sim$6500 cm^2 and a 1° field of view. In addition to the standard data modes, data were collected in the `GoodXenonwithPropane` mode, which records the arrival time (1 μs resolution) and energy (256-channel resolution) of every unrejected xenon event as well as all of the propane layer events. To maximize the sensitivity to the targets, which have soft spectra, we restricted the analysis to unrejected events in the top xenon layer of each PCU and chose an optimal energy range for each source: absolute channels[2] 6–14 (2.5–5.4 keV) for 1RXS J170849.0−400910 and absolute channels 6–24 (2.5–9.1 keV) for 1E 2259+586. The observations were reduced using MIT-developed software for handling raw spacecraft telemetry packet data. Data from the different PCUs were merged and binned at 62.5 ms and 31.25 ms resolution for 1RXS J170849.0−400910 and 1E 2259+586, respectively. The data were then reduced to Barycentric Dynamical Time (TDB) at the solar system barycenter using the source positions in Table 1 and the JPL DE200 solar system ephemeris (Standish et al. 1992) and stored on disk as one time series per observing epoch.

Our strategy for attempting phase-coherent timing of these sources made use of standard

[2]These channel-to-energy conversions are for *RXTE* gain epoch 3, from 1996 April 15 to 1999 March 22, averaged over the five PCUs.

radio pulsar techniques. Pulse phase at any time t can be expressed as

$$\phi(t) = \phi(t_0) + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + ..., \quad (1)$$

where t_0 is a reference epoch, and ν and $\dot{\nu}$ are the spin frequency and its time derivative. Phase-coherent timing amounts to counting all pulses over the entire observing span. To achieve this, uncertainties in the first-gues spin parameters ν and $\dot{\nu}$ must be sufficiently small that the discrepancy between observed and predicted arrival time differ by only a fraction of the period. To achieve this goal, we observed each source at two closely spaced epochs (i.e. within one day), then at a third epoch several days later. This spacing was chosen to determine an initial ν, by absolute pulse numbering, of sufficient precision to predict ϕ for the next observation roughly one month later. Subsequent monitoring was done at roughly one month intervals. Once phase connection was achieved with the $\sim$6 months of monitoring data, we also included public *RXTE* archival data. For 1RXS J170849.0−400910, the total data set consists of 19 arrival times obtained between 1998 January 13 and 1999 May 26. For 1E 2259+586, we have 33 arrival times obtained between 1996 September 29 and 1999 May 12.

Our procedure included the following steps. The first barycentered, binned time series for the closely spaced set of three observations were folded at the best-estimate period determined via Fourier transform, using a unique reference epoch. The folded pulse profiles were cross-correlated with a high-signal-to-noise template in the Fourier domain and the phase offsets were recorded. We suppressed high-order harmonics in the pulse profile using a frequency-domain filter to avoid contamination by bin-to-bin Poisson fluctuations. A precise ν was then determined by demanding that an integer number of pulses occur between each observation. Profiles were then re-folded, still with respect to a fixed epoch, using the improved ν. After each new observation, this process was repeated, also including the effect of $\dot{\nu}$. Phase residuals were examined to verify that there were no missed pulses, then fit with a quadratic function to determine the optimal ν and $\dot{\nu}$. Uncertainties on measured pulse phases were determined using Monte Carlo simulations. We verified this procedure and its results by extracting absolute average pulse arrival times in TDB at the solar system barycenter from the optimally folded profiles, and using the `TEMPO` pulsar timing software package (`http://pulsar.princeton.edu/tempo`), in common use in radio pulsar timing.

Best fit ν and $\dot{\nu}$ for each source are given in Table 1. These values were measured with $\ddot{\nu}$ fixed at zero. Corresponding arrival time residuals are shown in Figures 1 and 2. In both cases, the RMS residual is $\sim$0.01P, where $P = 1/\nu$. We also tried fitting for $\ddot{\nu}$; the results are given in Table 1. For 1E 2259+586, the fitted $\ddot{\nu}$ is consistent with zero; we provide a 3σ upper limit. For 1RXS J170849.0−400910, the fitted $\ddot{\nu}$ is marginally significant at the 4σ level; however, a fit omitting only the first point reduces the significance to 2.6σ. We

therefore quote the current best-fit value in parentheses only; further timing observations will decide if the observed $\ddot{\nu}$ is truly significant.

3. Discussion

Using a very simple spin-down model, we have maintained phase coherence for 1RXS J170849.0−400910 and 1E 2259+586 with phase residuals of only ∼1%, comparable to or smaller than those measured for most radio pulsars (e.g. Arzoumanian et al. 1994). This demonstrates that these AXPs are extremely stable rotators. This stability is consistent with the magnetar hypothesis because isolated rotating neutron stars are expected to spin-down with great regularity, as is seen in the radio pulsar population.

We can compare our pulse ephemerides with past period measurements to see whether there have been a deviation from a simple spin-down law. For 1RXS J170849.0−400910, only two previous period measurements have been reported (Sugizaki et al. 1997, Israel et al. 1999). The pulse parameters listed in Table 1, extrapolated to the epochs of the previous observations, agree with the published values within uncertainties. Thus, the spin-down has been regular for at least 1.4 yr prior to the commencement of our observations.

For 1E 2259+586, spin frequencies have been measured occasionally since 1978 (see Baykal & Swank 1996 and references therein). Figure 3 shows the differences between previously measured spin frequencies and those predicted by our timing ephemeris (Table 1). The error bars represent the published one standard deviation measurement uncertainties. Our measured $\dot{\nu}$ is not consistent with the long-term $\dot{\nu}$: all observed frequencies were significantly larger than predicted by the extrapolation of the current ν and $\dot{\nu}$. A least squares fit to the data shown in Figure 3 gives $\Delta\dot{\nu} = 1.328(9) \times 10^{-15}$ Hz s^{-1}, though the linear fit is poor because of apparent short-time-scale fluctuations. Thus, the current value of $\dot{\nu}$, measured over the past 2.6 yr, is smaller than that of the long-term trend by $\sim 10\%$.

Melatos (1999) suggests that the large magnetic field inferred in the magnetar model should result in significant deviations from sphericity of the neutron star, with the principle axis misaligned with the spin axis. Under such circumstances, the star undergoes radiative precession with period ∼10 yr. Given the epoch and duration of our observations of 1E 2259+586, the manifestation of such precession is completely covariant with $\dot{\nu}$. However, the implied deviation of $\dot{\nu}$ from the long-term trend is consistent with the Melatos (1999) prediction, though smaller by a factor ∼3.5. An unambiguous test of this model can be provided by periodic timing residuals on a time scale of a decade. Note that the change in $\dot{\nu}$ that we observe for 1E 2259+586 relative to the long-term trend is not consistent with those

observed after glitches in radio pulsars, in which the absolute magnitude of the post-glitch $\dot{\nu}$ is larger than the pre-glitch value (Shemar & Lyne 1996).

Radio pulsars, especially young ones, exhibit deviations from simple spin-down laws which appear to be a result of random processes (Cordes & Helfand 1980). These deviations are not physically understood and are commonly referred to as "timing noise" (see Lyne 1996 for a review). The measured $\ddot{\nu}$'s for 1RXS J170849.0−400910 and 1E 2259+586 (Table 1) can be compared with those of radio pulsars. Noise level has been quantified by Arzoumanian et al. (1994) by the statistic $\Delta_8 \equiv \log\left(|\ddot{\nu}|t^3/6\nu\right)$, for $t = 10^8$ s. We find $\Delta_8 \leq 1.7$ and < 0.5 for 1RXS J170849.0−400910 and 1E 2259+586, respectively. These values place these objects clearly among the radio pulsar population on the Δ_8–$\dot{P}$ plot of Arzoumanian et al. (1994), as was suggested for 1E 2259+586 and 1E 1048.1−5937 by Heyl & Hernquist (1997) on the basis of sparser, incoherent data. Torque noise in the accreting pulsar population would generally predict much larger values of $\ddot{\nu}$ (Bildsten et al. 1997, although see also Chakrabarty et al. 1997). One caveat is that the 8 s accreting X-ray pulsar 4U 1626−67 is known to be in a close binary orbit with a low-mass companion, with orbital period 42 min (Middleditch et al. 1981, Chakrabarty 1998). The X-ray pulsations show no Doppler shifts (Levine et al. 1988, Chakrabarty et al. 1997), implying that we are viewing the orbit nearly face-on. Timing observations of 4U 1626−67 over $\sim$8 yr permit phase-coherent timing, except near one epoch where the spin-down rate abruptly changed sign (Chakrabarty et al. 1997). The apparent change in spin-down rate we have detected for 1E 2259+586 is plausible as a change in accretion torque. However, if the X-rays observed for the two AXPs considered here had an accretion origin, the orbits must both be viewed face-on as well, which is unlikely. Furthermore the much harder X-ray spectrum of 4U 1626−67 (Owens, Oosterbroek, & Parmar 1997), which is consistent with other accreting sources, is very different from those of any of the known AXPs, including 1RXS J170849.0−400910 and 1E 2259+586.

An alternative model for AXPs, that they are massive white dwarfs, also predicts regular spin down (Paczynski 1990). In this model, the larger moment of inertia hence larger spin-down luminosity accounts for the observed L_x. However, if the observed X-rays have a thermal origin, e.g. emission from hot gas heated by positrons near the polar cap (Usov 1993), the implied hot spot is implausibly small (Thompson & Duncan 1996). Also, data obtained with the EGRET instrument aboard the *Compton Gamma-Ray Observatory* show (D. Thompson, personal communication) that the high-energy γ-ray flux from 1E 2259+586 is smaller than predicted in the white dwarf model (Usov 1993). Furthermore, an observable supernova remnant, as is seen surrounding 1E 2259+586 (CTB 109), is not expected for a white dwarf. Note that the absence of a possibly associated supernova remnant is not evidence against an AXP being a young neutron star, given the limited observability of some

remnants associated with very young pulsars (e.g. Braun, Goss, & Lyne 1989, Pivovaroff, Kaspi & Gotthelf 1999).

With the stability of the rotation of 1RXS J170849.0−400910 and 1E 2259+586 established, the door is now open for unambiguously testing the magnetar model. In particular, although neither source has glitched during our observations, which implies glitch activity lower than in some comparably young radio pulsars (e.g. Kaspi et al. 1992, Shemar & Lyne 1996), future glitches will be easily identified. Also, for 1RXS J170849.0−400910, a braking index of 3, expected if the source is spinning down due to magnetic dipole radiation, should be measurable in another year, although its measurement could be complicated by timing noise, precessional effects and/or glitches. The periodic precession predicted by Melatos (1999) could be clearly confirmed or ruled out in the next few years of *RXTE* monitoring, particularly if earlier observations made with other observatories can be incorporated.

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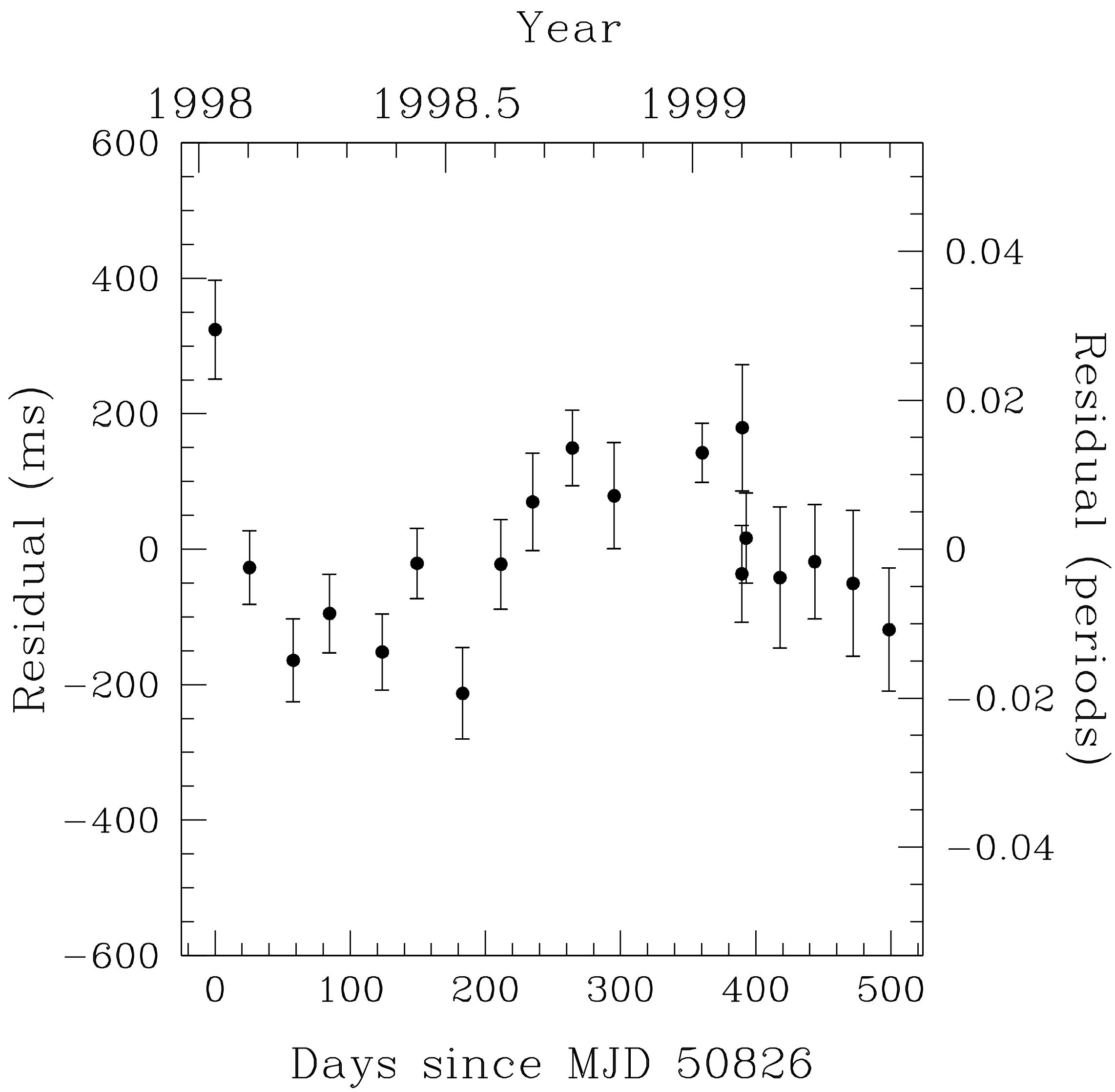

Fig. 1.— Arrival time residuals for 1RXS J170849.0−400910 versus epoch. Note that the vertical axis represents only ±5% of the pulse period, indicating high rotational stability.

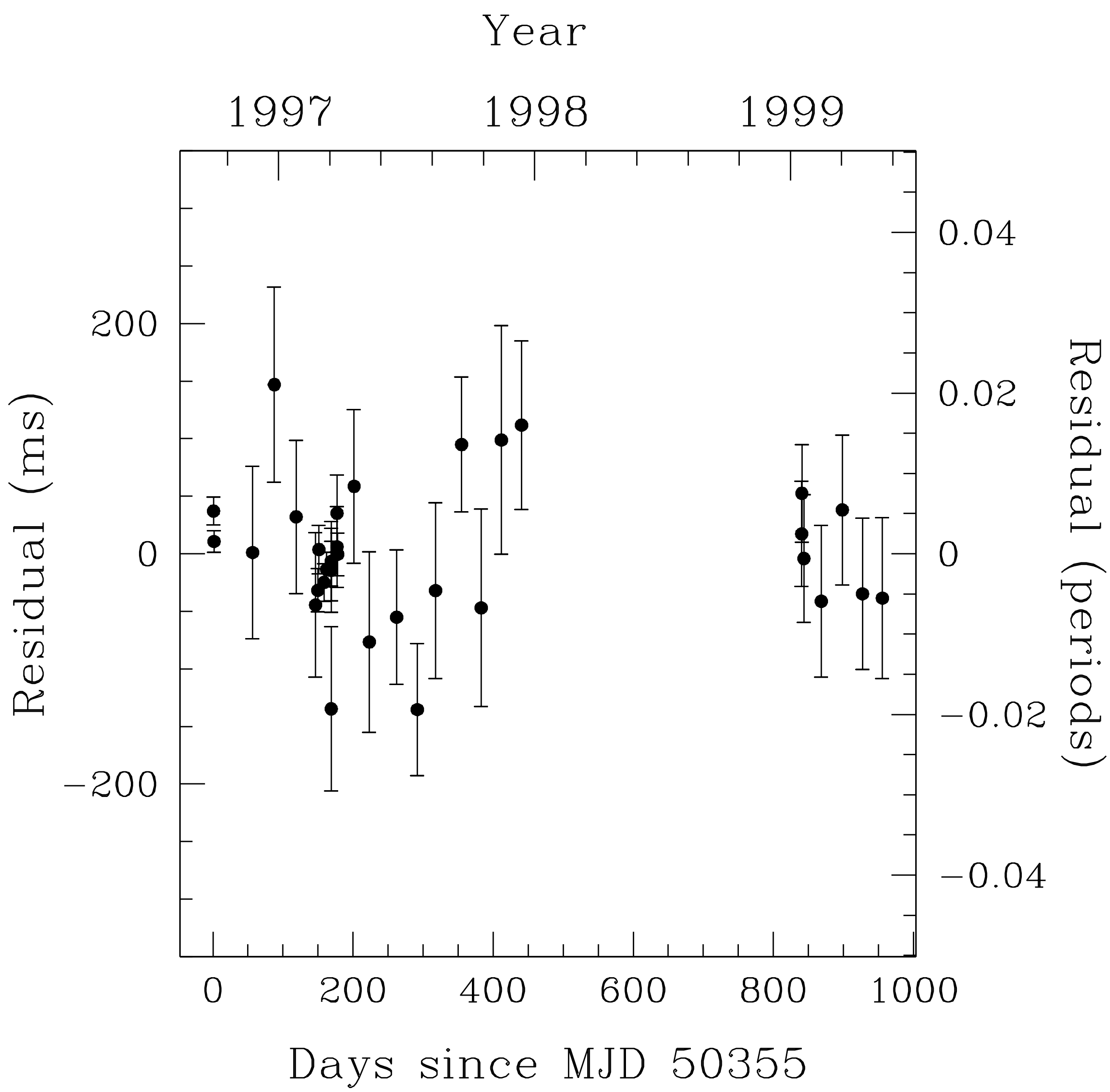

Fig. 2.— Arrival time residuals for 1E 2259+586 versus epoch. Note that the vertical axis represents only ±5% of the pulse period, indicating high rotational stability.

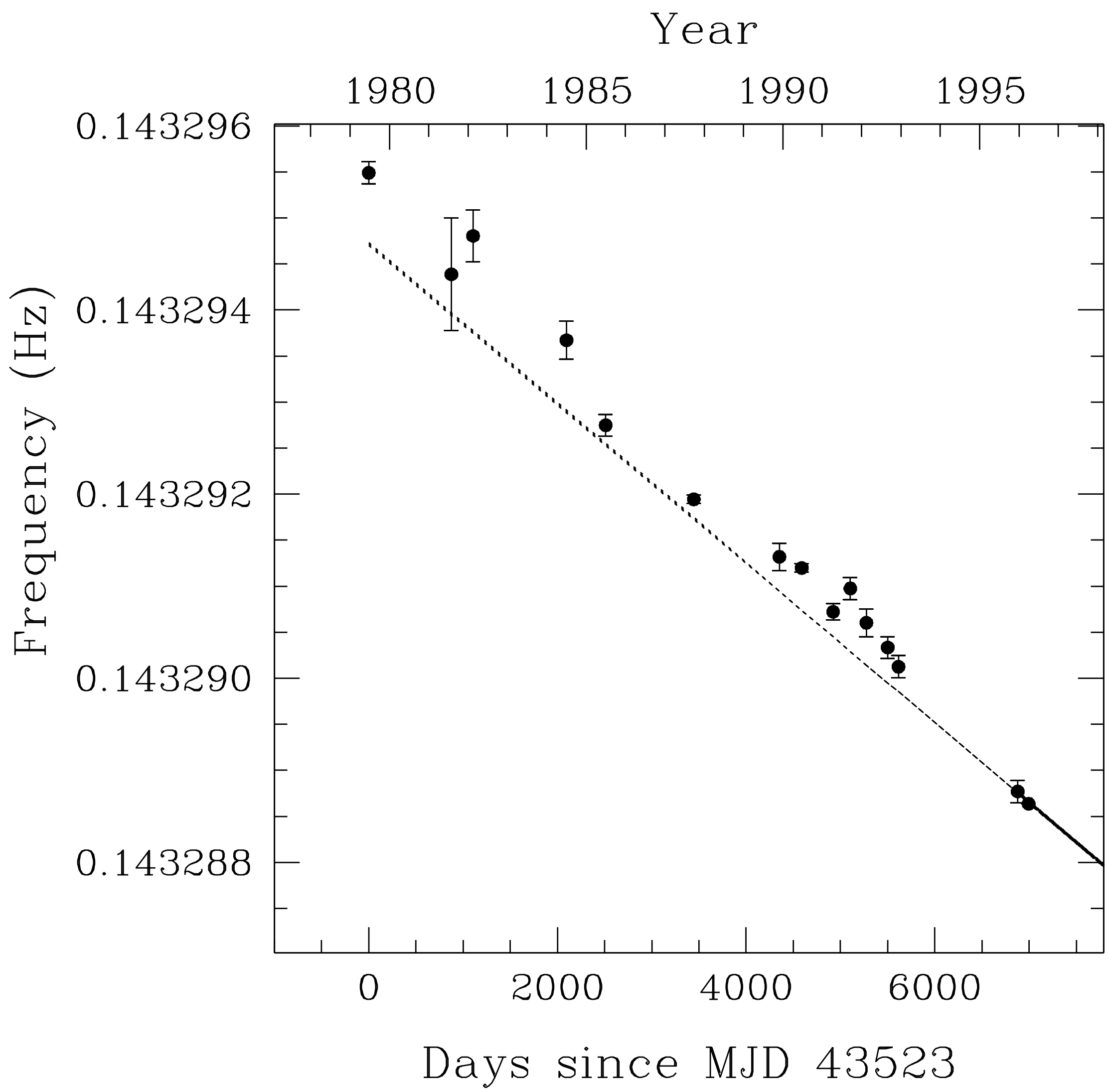

Fig. 3.— Previously observed spin frequencies for 1E 2259+586 (see Baykal & Swank 1996 and references therein) and the ephemeris obtained from phase-coherent *RXTE* observations described in this paper (see Table 1). The epochs over which the *RXTE* observations were made are indicated with a solid line; previously observed frequencies that are consistent with our spin ephemeris should fall on the dotted line. The uncertainty in the extrapolation is comparable the width of the dotted line. That the previously measured frequencies fall above the line implies that the $\dot{\nu}$ measured over 2.6 yr from the phase-coherent observations is not consistent with the long-term $\dot{\nu}$. See text for discussion.

Table 1. Parameters for Observed Anomalous X-ray Pulsars[a]

	1RXS J170849.0−400910	1E 2259+586
R.A. (J2000)	$17^{\mathrm{h}}\ 08^{\mathrm{m}}\ 47^{\mathrm{s}}$	$23^{\mathrm{h}}\ 01^{\mathrm{m}}\ 07^{\mathrm{s}}.9$
DEC (J2000)	$-40^\circ\ 08'\ 51''$	$+58^\circ\ 52'\ 46''$
First Observing Epoch (MJD)	50826	50355
Last Observing Epoch (MJD)	51324	51310
Total Number of Observations	19	33
ν (Hz)	0.0909169331(5)	0.1432880613(2)
$\dot{\nu}$ (10^{-14} Hz s^{-1})	−15.687(4)	−1.0026(7)
$\ddot{\nu}$ (10^{-24} Hz s^{-2})	[29(7)]	[2.3(1.0)]
P (s)	10.99905117(6)	6.97894850(1)
$\dot{P}$ (10^{-13})	189.78(5)	4.883(3)
Epoch of ν (MJD)	51215.931	51195.583
R.M.S. residual (ms)	129	61

[a] *ROSAT* HRI position for 1RXS J170849.0−400910 from Israel et al. (1999). Position for 1E 2259+586 from Fahlman et al. (1982). Numbers in parentheses are 1σ statistical uncertainties in the last digit. The measured $\ddot{\nu}$ for 1RXS J170849.0−400910 is marginal (see text).